Appendix D
Cleanup Technologies

Exhibit D-1 Table of Cleanup Technologies

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Containment Technologies				
Capping	• Used to cover buried waste materials to prevent migration.Consist of a relatively impermeable material that will minimize rainfall infiltration.Waste materials can be left in place.Requires periodic inspections and routine monitoring.Contaminant migration must be monitored periodically.	• MetalsCyanide	• Costs associated with routine sampling and analysis may be high.Long-term maintenance may be required to ensure impermeability.May have to be replaced after 20 to 30 years of operation.May not be effective if groundwater table is high.	• $11 to $40 per square foot.[1]
Sheet Piling	• Steel or iron sheets are driven into the ground to form a subsurface barrier.Low-cost containment method.Used primarily for shallow aquifers.	• Not contaminant-specific	• Not effective in the absence of a continuous aquitard.Can leak at the intersection of the sheets and the aquitard or through pile wall joints.	• $8 to $17 per square foot.[2]
Grout Curtain	• Grout curtains are injected into subsurface soils and bedrock.Forms an impermeable barrier in the subsurface.	• Not contaminant-specific	• Difficult to ensure a complete curtain without gaps through which the plume can escape; however new techniques have improved continuity of curtain.	• $6 to $14 per square foot.[2]

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Slurry Walls	• Used to contain contaminated ground water, landfill leachate, divert contaminated groundwater from drinking water intake, divert uncontaminated groundwater flow, or provide a barrier for the groundwater treatment system.Consist of a vertically excavated slurry-filled trench.The slurry hydraulically shores the trench to prevent collapse and forms a filtercake to reduce groundwater flow.Often used where the waste mass is too large for treatment and where soluble and mobile constituents pose an imminent threat to a source of drinking threat to a source of drinking water.Often constructed of a soil, bentonite, and water mixture.	• Not contaminant-specific	• Contains contaminants only within a specified area.Soil-bentonite backfills are not able to withstand attack by strong acids, bases, salt solutions, and some organic chemicals.Potential for the slurry walls to degrade or deteriorate over time.	• Design and installation costs of $5 to $7 per square foot (1991 dollars) for a standard soil-bentonite wall in soft to medium soil.[3]Above costs do not include variable costs required for chemical analyses, feasibility, or compatibility testing.
Ex Situ Technologies				
Excavation/Offsite Disposal	• Removes contaminated material to an EPA approved landfill.	• Not contaminant-specific	• Generation of fugitive emissions may be a problem during operations.The distance from the contaminated site to the nearest disposal facility will affect cost.Depth and composition of the media requiring excavation must be considered.Transportation of the soil through populated areas may affect community acceptability.Disposal options for certain waste (e.g., mixed waste or transuranic waste) may be limted. There is currently only one licensed disposal facility for radioactive and mixed waste in the United States.	• $270 to $460 per ton.[2]

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Composting	• Controlled microbiological process by which biodegradable hazardous materials in soils are converted to innocuous, stabilized byproducts.Typically occurs at temperatures ranging from 50° to 55°C (120° to 130°F).May be applied to soils and lagoon sediments.Maximum degradation efficiency is achieved by maintaining moisture content, pH, oxygenation, temperature, and the carbon-nitrogen ratio.	• SVOCs.	• Substantial space is required. Excavation of contaminated soils is required and may cause the uncontrolled release of VOCs.Composting results in a volumetric increase in material and space required for treatment.Metals are not treated by this method and can be toxic to the microorganisms.The distance from the contaminated site to the nearest disposal facility will affect cost.	• $190 or greater per cubic yard for soil volumes of approximately 20,000 cubic yards.[3]Costs will vary with the amount of soil to be treated, the soil fraction of the com post, availability of amendments, the type of contaminant and the type of process design employed.
Chemical Oxidation/ Reduction	• Reduction/oxidation (Redox) reactions chemically convert hazardous contaminants to nonhazardous or less toxic compounds that are more stable, less mobile, or inert.Redox reactions involve the transfer of electrons from one compound to another.The oxidizing agents commonly used are ozone, hydrogen peroxide, hypochlorite, chlorine, and chlorine dioxide.	• MetalsCyanide	• Not cost-effective for high contaminant concentrations because of the large amounts of oxidizing agent required.Oil and grease in the media should be minimized to optimize process efficiency.	• $190 to $660 per cubic meter of soil.[3]
Soil Washing	• A water-based process for scrubbing excavated soils ex situ to remove contaminants.Removes contaminants by dissolving or suspending them in the wash solution, or by concentrating them into a smaller volume of soil through particle size separation, gravity separation, and attrition scrubbing.Systems incorporating most of the removal techniques offer the greatest promise for application to soils contaminated with a wide variety of metals and organic contaminants.	• SVOCsMetals	• Fine soil particles may require the addition of a polymer to remove them from the washing fluid.Complex waste mixtures make formulating washing fluid difficult.High humic content in soil may require pretreatment.The washing fluid produces an aqueous stream that requires treatment.	• $120 to $200 per ton of soil.[3]Cost is dependent upon the target waste quantity and concentration.

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Thermal Desorption	• Low temperatures (200°F to 900°F) are used to remove organic contaminants from soils and sludges.Off-gases are collected and treated. Requires treatment system after heating chamber.Can be performed on site or off site.	• VOCsPCBsPAHs	• Cannot be used to treat heavy metals, with exception of mercury.Contaminants of concern must have a low boiling point.Transportation costs to off-site facilities can be expensive.	• $50 to $300 per ton of soil.[3]Transportation charges are additional.
Incineration	• High temperatures 870° to 1,200° C (1400°F to 2,200°F) are used to volatilize and combust hazardous wastes.The destruction and removal efficiency for properly operated incinerators exceeds the 99.99% requirement for hazardous waste and can be operated to meet the 99.9999% requirement for PCBs and dioxins.Commercial incinerator designs are rotary kilns, equipped with an afterburner, a quench, and an air pollution control system.	• VOCsPCBsdioxins	• Only one off-site incinerator is permitted to burn PCBs and dioxins. Specific feed size and materials handling requirements that can affect applicability or cost at specific sites.Metals can produce a bottom ash that requires stabilization prior to disposal.Volatile metals, including lead, cadmium, mercury, and arsenic, leave the combustion unit with the flue gases and require the installation of gas cleaning systems for removal.Metals can react with other elements in the feed stream, such as chlorine or sulfur, forming more volatile and toxic compounds than the original species.	• $200 to $1,000 per ton of soil at off-site incinerators.$1,500 to $6,000 per ton of soil for soils contaminated with PCBs or dioxins.[3]Mobile units that can operate onsite reduce soil transportation costs.
UV Oxidation	• Destruction process that oxidizes constituents in wastewater by the addition of strong oxidizers and irradiation with UV light.Practically any organic contaminant that is reactive with the hydroxyl radical can potentially be treated. The oxidation reactions are achieved through the synergistic action of UV light in combination with ozone or hydrogen peroxide.Can be configured in batch or continuous flow models, depending on the throughput rate under consideration.	• VOCs	• The aqueous stream being treated must provide for good transmission of UV light (high turbidity causes interference).Metal ions in the wastewater may limit effectiveness.VOCs may volatilize before oxidation can occur. Off-gas may require treatment.Costs may be higher than competing technologies because of energy requirements.Handling and storage of oxidizers require special safety precautions.Off-gas may require treatment.	• $0.10 to $10 per 1,000 gallons are treated.[3]

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Pyrolysis	• A thermal treatment technology that uses chemical decomposition induced in organic materials by heat in the absence of oxygen. Pyrolysis transforms hazardous organic materials into gaseous components, small amounts of liquid, and a solid residue (coke) containing fixed carbon and ash.	• MetalsCyanide. PAHs	• Specific feed size and materials handling requirements affect applicability or cost at specific sites.Requires drying of the soil to achieve a low soil moisture content (<1%).Highly abrasive feed can potentially damage the processor unit.High moisture content increases treatment costs.Treated media containing heavy metals may require stabilization.May produce combustible gases, including carbon monoxide, hydrogen and methane, and other hydrocarbons.If the off-gases are cooled, liquids condense, producing an oil/tar residue and contaminated water.	• Capital and operating costs are expected to be approximately $330 per metric ton ($300 per ton).[3]
Precipitation	• Involves the conversion of soluble heavy metal salts to insoluble salts that will precipitate.Precipitate can be physical methods such as clarification or filtration.Often used as a pretreatment for other treatment technologies where the presence of metals would interfere with the treatment processes.Primary method for treating metal-laden industrial wastewater.	• Metals.	• Contamination source is not removed.The presence of multiple metal species may lead to removal difficulties.Discharge standard may necessitate further treatment of effluent.Metal hydroxide sludges must pass TCLP criteria prior to land disposal.Treated water will often require pH adjustment.	• Capital costs are $85,000 to $115,000 for 20 to 65 gpm precipitation systems.Primary capital cost factor is design flow rate.Operating costs are $0.30 to $0.70 per 1,000.[3] Sludge disposal may be estimated to increase operating costs by $0.50 per 1,000 gallons treated.[3]

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Liquid Phase Carbon Adsorption	• Groundwater is pumped through a series of vessels containing activated carbon, to which dissolved contaminants adsorb.Effective for polishing water discharges from other remedial technologies to attain regulatory compliance.Can be quickly installed.High contaminant-removal efficiencies.	• Low levels of metals.VOCs.SVOCs.	• The presence of multiple contaminants can affect process performance.Metals can foul the system.Costs are high if used as the primary treatment on waste streams with high contaminant concentration levels.Type and pore size of the carbon and operating temperature will impact process performance.Transport and disposal of spent carbon can be expensive.Water soluble compounds and small molecules are not adsorbed well.	• $1.20 to $6.30 per 1,000 gallons treated at flow rates of 0.1 mgd.Costs decrease with increasing low rates and concentrations.[3]Costs are dependent on waste stream flow rates, type of contaminant, concentration, and timing requirements.[3]
Air Stripping **In Situ Technologies**	• Contaminants are partitioned from groundwater by greatly increasing the surface area of the contaminated water exposed to air.Aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.Can be operated continuously or in a batch mode, where the air stripper is intermittently fed from a collection tank.The batch mode ensures consistent air stripper performance and greater efficiency than continuously operated units because mixing in the storage tank eliminates any inconsistencies in feed water composition.	• VOCs.	• Potential for inorganic (iron greater than 5 ppm, hardness greater than 800 ppm) or biological fouling of the equipment, requiring pretreatment of groundwater or periodic column cleaning.Consideration should be given to the Henry's law constant of the VOCs in the water stream and the type and amount of packing used in the tower.Compounds with low volatility at ambient temperature may require preheating of the groundwater.Off-gases may require treatment based on mass emission rate and state and federal air pollution laws.	• $0.04 to $0.20 per 1,000 gallons.[3]A major operating cost of air strippers is the electricity required for the groundwater pump, the sump discharge pump, and the air blower.

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Natural Attenuation	• Natural subsurface processes such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface media can reduce contaminant concentrations to acceptable levels.Consideration of this option requires modeling and evaluation of contaminant degradation rates and pathways.Sampling and analyses must be conducted throughout the process to confirm that degradation is proceeding at sufficient rates to meet cleanup objectives.Nonhalogenated volatile and semivolatile organic compounds.	• VOCs	• Intermediate degradation products may be more mobile and more toxic than original contaminants.Contaminants may migrate before they degrade.The site may have to be fenced and may not be available for reuse until hazard levels are reduced.Source areas may require removal for natural attenuation to be effective.Modeling contaminant degradation rates, and sampling and analysis to confirm modeled predictions extremely expensive.	• Not available
Soil Vapor Extraction	• A vacuum is applied to the soil to induce controlled air flow and remove contaminants from the unsaturated (vadose) zone of the soil.The gas leaving the soil may be treated to recover or destroy the contaminants.The continuous air flow promotes in situ biodegradation of low-volatility organic compounds that may be present.	• VOCs	• Tight or very moist content (>50%) has a reduced permeability to air, requiring higher vacuums.Large screened intervals are required in extraction wells for soil with highly variable permeabilities.Air emissions may require treatment to eliminate possible harm to the public or environment.Off-gas treatment residual liquids and spent activated carbon may require treatment or disposal.Not effective in the saturated zone.	• $10 to $50 per cubic meter of soil.[3]Cost is site specific depending on the size of the site, the nature and amount of contamination, and the hydro-geological setting, which affect the number of wells, the blower capacity and vacuum level required, and length of time required to remediate the site.Off-gas treatment significantly adds to the cost.

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Soil Flushing	• Extraction of contaminants from the soil with water or other aqueous solutions.Accomplished by passing the extraction fluid through in-place soils using injection or infiltration processes.Extraction fluids must be recovered with extraction wells from the underlying aquifer and recycled when possible.	• Metals	• Low-permeability soils are difficult to treat.Surfactants can adhere to soil and reduce effective soil porosity.Reactions of flushing fluids with soil can reduce contaminant mobility.Potential of washing the contaminant beyond the capture zone and the introduction of surfactants to the subsurface.	• The major factor affecting cost is the separation of surfactants from recovered flushing fluid.[3]
Solidification/ Stabilization	• Reduces the mobility of hazardous substances and contaminants through chemical and physical means.Seeks to trap or immobilize contaminants within their “host” medium, instead of removing them through chemical or physical treatment.Can be used alone or combined with other treatment and disposal methods.	• MetalsLimited effectiveness for VOCs and SVOCs.	• Depth of contaminants may limit effectiveness.Future use of site may affect containment materials, which could alter the ability to maintain immobilization of contaminants.Some processes result in a significant increase in volume.Effective mixing is more difficult than for ex situ applications.Confirmatory sampling can be difficult.	• $50 to $80 per cubic meter for shallow applications.$190 to $330 per cubic meter for deeper applications.[3]Cost s for cement-based stabilization techniques vary according to materials or reagents used, their availability, project size, and the chemical nature of the contaminant.

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Air Sparging	• In situ technology in which air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of contaminants by naturally occurring microbes.Increases the mixing in the saturated zone, which increases the contact between groundwater and soil. Air bubbles traverse horizontally and vertically through the soil column, creating an underground stripper that removes contaminants by volatilization.Air bubbles travel to a soil vapor extraction system.Air sparging is effective for facilitating extraction of deep contamination, contamination in low-permeability soils, and contamination in the saturated zone.	• VOCs	• Depth of contaminants and specific site geology must be considered.Air flow through the saturated zone may not be uniform.A permeability differential such as a clay layer above the air injection zone can reduce the effectiveness.Vapors may rise through the vadose zone and be released into the atmosphere.Increased pressure in the vadose zone can build up vapors in basements, which are generally low-pressure areas.	• $50 to $100 per 1,000 gallons of groundwater treated.[3]
Passive Treatment Walls	• A permeable reaction wall is installed inground, across the flow path of a contaminant plume, allowing the water portion of the plume to passively move through the wall.Allows the passage of water while prohibiting the movement of contaminants by employing such agents as iron, chelators (ligands selected for their specificity for a given metal), sorbents, microbes, and others.Contaminants are typically completely degraded by the treatment wall.	• MetalsVOCs	• The system requires control of pH levels. When pH levels within the passive treatment wall rise, it reduces the reaction rate and can inhibit the effectiveness of the wall.Depth and width of the plume. For large-scale plumes, installation cost may be high.Cost of treatment medium (iron).Biological activity may reduce the permeability of the wall.Walls may lose their reactive capacity, requiring replacement of the reactive medium.	• Capital costs for these projects range from $250,000 to $1,000,000.[3]Operations and maintenance costs approximately 5 to 10 times less than capital costs.
Chemical Oxidation	• Destruction process that oxidizes constituents in groundwater by the addition of strong oxidizers.Practically any organic contaminant that is reactive with the hydroxyl radical can potentially be treated.	• VOCs	• The addition of oxidizing compounds must be hydraulically controlled and closely monitored.Metal additives will precipitate out of solution and remain in the aquifer.Handling and storage of oxidizers require special safety precautions.	• Depends on mass present and hydrogeologic conditions.[3]

Exhibit D-1 Table of Cleanup Technologies (continued)

Applicable Technology	Technology Description	Contaminants Treated by this Technology	Limi	Cost
Bioventing	• Stimulates the natural in-situ biodegradation of volatile organics in soil by providing oxygen to existing soil microorganisms.Oxygen commonly supplied through direct air injection.Uses low air flow rates to provide only enough oxygen to sustain microbial activity.Volatile compounds are biodegraded as vapors and move slowly through the biologically active soil.	• VOCs.	• Low soil-gas permeability.High water table or saturated soil layers.Vapors can build up in basements within the radius of influence of air injection wells.Low soil moisture content may limit biodegradation by drying out the soils.Low temperatures slow remediation.Chlorinated solvents may not degrade fully under certain subsurface conditions.Vapors may need treatment, depending on emission level and state regulations.	• $10 to $70 per cubic meter of soil.[3]Cost affected by contaminant type and concentration, soil permeability, well spacing and number, pumping rate, and off-gas treatment.
Biodegradation	• Indigenous or introduced microorganisms degrade organic contaminants found in soil and groundwater.Used successfully to remediate soils, sludges, and groundwater.Especially effective for remediating low-level residual contamination in conjunction with source removal.	• VOCs.	• Cleanup goals may not be attained if the soil matrix prevents sufficient mixing.Circulation of water-based solutions through the soil may increase contaminant mobility and necessitate treatment of underlying groundwater. • Injection wells may clog and prevent adequate flow rates.Preferential flow paths may result in nonuniform distribution of injected fluids.Should not be used for clay, highly layered, or heterogeneous subsurface environments.High concentrations of heavy metals, highly chlorinated organics, long chain hydrocarbons, or inorganic salts are likely to be toxic to microorganisms.Low temperatures slow bioremediation.Chlorinated solvents may not degrade fully under certain subsurface conditions.	• $30 to $100 per cubic meter of soil.[3]Cost affected by the nature and depth of the contaminants, use of bioaugmentation or hydrogen peroxide addition, and groundwater pumping rates.

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Oxygen Releasing Compounds	• Based on Fenton's Reagent Chemistry.Stimulates the natural in situ biodegradation of petroleum hydrocarbons in soil and groundwater by providing oxygen to existing microorganisms.Oxygen supplied through the controlled dispersion and diffusion of active reagents, such as hydrogen peroxide.Active reagents are injected into the affected area using semi-permanent injection wells.	• TPHsVOCs	• Low soil permeability limits dispersion.Low soil moisture limits reaction time.Low temperatures slow reaction.Not cost-effective in the presence of unusually thick layers of free product.	• Relatively low cost in applications on small areas of contamination. Cost depends on size of treatment area and amount of contaminant present as free product.

1. Interagency Cost Workgroup, 1994.
2. Costs of Remedial Actions at Uncontrolled Hazardous Waste Sites, U.S. EPA, 1986.
3. Federal Remediation Technology Roundtable. Http://www.frtr.gov/matrix/top_page.html

UST = underground storage tank
SVOCs = semi-volatile organic compounds
VOCs = volatile organic compounds
PAHs = polyaromatic hydrocarbons
PCBs = polychlorinated biphenyls
TPH = total petroleum hydrocarbons